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TESTING AND ANALYSIS OF THE SEMISCALE MOD-1 HEATER ROD DESIGN

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by

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ABSTRACT

The use of electrically heated nuclear fuel rod simulators in the Semiscale Program is traced from a historical viewpoint. The design of the Semiscale Mod-1 electrical heater rod and core simulator is discussed. Heater rod thermal response during transient thermal-hydraulic depressurization experiments conducted in the Mod-1 system, and analysis techniques and tests conducted to help quantify heater rod characteristics and behavior are presented.

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INTRODUCTION

Experimental facilities are widely used in the nuclear reactor safety industry. Usually, these facilities produce separate effects and integral system thermal-hydraulic data that are used in the development and assessment of computer codes used to predict the consequences of off-normal operation or hypothesized occurrences in pressurized water reactors (PWRs). These experimental facilities usually have a heat generation source to provide for coolant heating and the attainment of pressure and temperature conditions similar to a PWR. Many such experimental systems use nuclear core simulators composed of electrical resistance heaters rather than actual nuclear fuel rods for obvious reasons such as safety considerations, ease of operation, etc. The Semiscale Program, which is conducted at the Idaho National Engineering Laboratory by EG&G Idaho, Inc., for the United States Nuclear Regulatory Commission and the Department of Energy, has used electrical resistance heaters for more than a decade in the various Semiscale systems used to conduct nuclear reactor safety research. These resistance heaters have been used for a variety of purposes - especially in the simulation of nuclear fuel bundles. The heater rods used in the various Semiscale systems have been subjected to a variety of special testing procedures in addition to the normal transient experiments conducted as a part of the nuclear safety research program. As a result, considerable experience has been gained regarding electrical heater rod design, reliability, control, and analysis.

The remainder of this paper deals particularly with the experience that has been gained regarding the use of fuel rod simulators in the Semiscale Program. For completeness, a brief history of the Program is given and the designs of the different heaters used over the years are discussed. Finally, the testing and analysis done on the most current rod design are addressed.

HISTORICAL BACKGROUND

The first generation, heated core Semiscale facility (known as Single Loop Semiscale)[1] was operated from 1969 to 1971. This facility was used to perform numerous depressurization transients (blowdowns) to investigate system mechanical response, as well as emergency core coolant (ECC) delivery behavior. Core heat in this facility was simulated by an array of 121, 1.118-cm-diameter, 23-cm-long rods, arranged in a 2.461-cm triangular pitch. The total electrical power capability of this system was 1.5 MW. Although a considerable amount of useful data was obtained from the experiments conducted in this facility, the core and other components were not well scaled geometrically or kinematically.

A new system, the Semiscale 1-1/2 Loop system was constructed in 1971. This system had a 1.68-m-long core composed of 32, 1.07-cm-diameter rods arranged on a 1.43-cm pitch. Except for the length, which was based on the Loss-of-Fluid Test[2] (LOFT) fuel bundle, the rod diameter and pitch spacing were typical of PWR fuel. Only limited testing was performed in this facility because the bundle was burned out during checkout testing. The core problems were traced to numerous causes, including cladding surface thermocouple mounting and welding techniques and the core power supply design. The welds on the thermocouples were thought to leak and promote moisture absorption by the material insulating the resistance filament from the metal cladding. The leakage path was then an avenue for the rod to fail by electrical shorting from the filament to the cladding. The power supply was designed so that when a rod (or rods) failed, the remaining intact rods absorbed the extra power available. In this fashion, many of the rods were thought to have been overpowered from a design maximum linear heat rate of 62 kW/m to as much as 131 kW/m. Such overpowering was speculated to have caused resistance filament melting and eventual rod failure.

A redesign of the heaters, power supply, vessel, loops, and steam generator resulted in a system known as Semiscale Mod-1,[3] completed in 1974. Like the Semiscale 1-1/2 Loop system, this facility had 1.68-m-long rods of typical PWR pitch spacing and diameter. The cladding thermocouple installation and the power supply were, however, quite different than the 1-1/2 loop system. (The design will be discussed in more detail in the next section.) More than 50 blowdown-type tests and 12 separate effects reflood tests were conducted in the Mod-1 system.[4] The heater rod response and cladding temperature behavior during these experiments provided a large data base for rod behavior investigations.

The Mod-3[5] Semiscale system replaced the Mod-1 system in 1977. The heater rods in this system were basically identical to the Mod-1 rods, with the exception of the length and axial power profile. Both rod designs had an axially stepped, cosine power profile, but the Mod-3 rods were 3.66 m in length and the Mod-1 rods, as discussed above, were 1.68 m in length. Also, the Mod-3 rods had an axial peak-to-average power ratio of 1.55, whereas the Mod-1 rods had a peak-to-average power ratio of 1.58. Many experiments, including large break blowdown (3), reflood (3), large break integral blowdown-reflood (4), small break (12), and Three Mile Island transient simulation (10), have been conducted with the Mod-3 system.[6] The heater rods have proven to be both durable and reliable during the conduct of these tests.

SEMISCALE HEATER ROD DESIGNS

Three basic heater rod designs have been used in the Semiscale Program. The design and operating conditions for these rods are described in this section.

23-cm Heater Rods

The configuration and heater rod design used for the core configuration in the Semiscale Single Loop Test Facility are shown in Figure 1. The electrically heated core consisted of 121 heaters arranged in a triangular pitch of 2.461 cm, as shown in Figure 1. The heaters were cartridge types, consisting of 23-cm Nichrome resistance elements located 15.24 cm from one end of 165-cm-long, 1.118-cm-diameter (OD), 0.165-cm-thick, Inconel sheaths. The heating element was insulated with boron nitride and the remainder of the cartridge was insulated with magnesium oxide. The heaters had a flat axial power profile and were capable of operating at a linear heat rate of 54 kW/m. Twenty of the heater rods were instrumented with four Chromel-Alumel thermocouples located within the sheath and with one Chromel-Alumel thermocouple located on the interior of the sheath. The thermocouples within the sheath were swaged in grooves milled in the sheath, whereas the interior thermocouples were placed against the sheath with the lead wires routed through the insulation.

1.68-m Heater Rods

The heater rod bundle used in the Semiscale 1-1/2 Loop system consisted of 32 heaters, as shown in Figure 2, whereas the bundle used in the Semiscale Mod-1 system consisted of 40 heaters, as depicted in Figure 3. The rods in both systems had 1.68-m-long heated lengths and were of similar construction except for the sheath (cladding) design and thermocouple installation technique. The Mod-1 rod construction is shown in Figure 4. The overall length of the rods was about 526 cm, extending from the bottom of the heated section to the vessel upper plenum where they passed out the vessel upper head. The rods were of typical PWR fuel rod diameter (1.08 cm) and pitch (1.43 cm).

The rod heating element was constructed of constantan wire (55% copper, 45% nickel), coiled with a varying pitch, and sized (either AWG #12 or #14) to develop the specified axially stepped, chopped cosine power profile shown in Figure 5. The axial power peaking factor of the rods was 1.58. Compacted boron nitride surrounded the element and insulated it from a composite sheath (0.089 cm thick). A mica moisture seal was located at the heater terminal end. The filament was brazed to the lead-in conductor and to the ground lead extension. A 2.54-cm square tab was brazed to the top end of each lead-in conductor, and the copper cables from the power supply were bolted to the tabs. The grounding plug was welded to the ground lead extension and to the composite sheath, and the ground lead extension was threaded to provide for termination of a copper grounding wire. The composite sheath (Figure 4) was manufactured from 316L stainless steel. The inner sheath was creased along the total rod length (concavely) at four locations spaced azimuthally around the rod circumference to accept four, 0.064-cm-diameter, laser beam tack welded thermocouple assemblies. The thermocouple leads exited the heater assembly at the heater terminal end (Figure 4). The creases from the

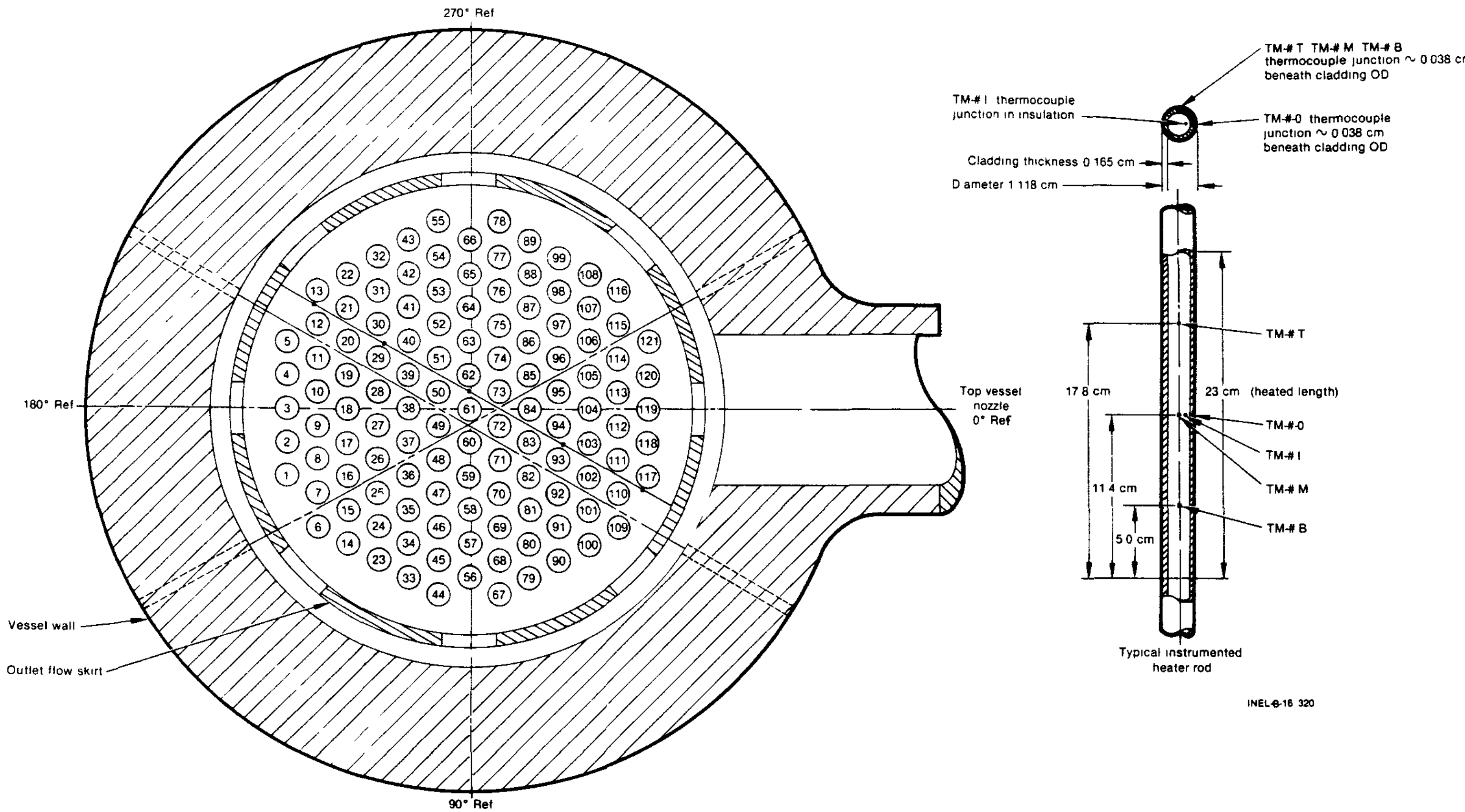

Figure 1. Heater rod and thermocouple locations.

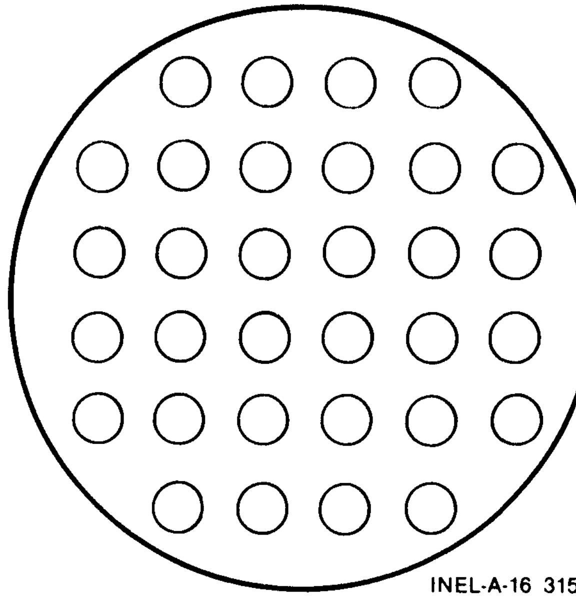

Figure 2. Semiscale 1-1/2 Loop core configuration.

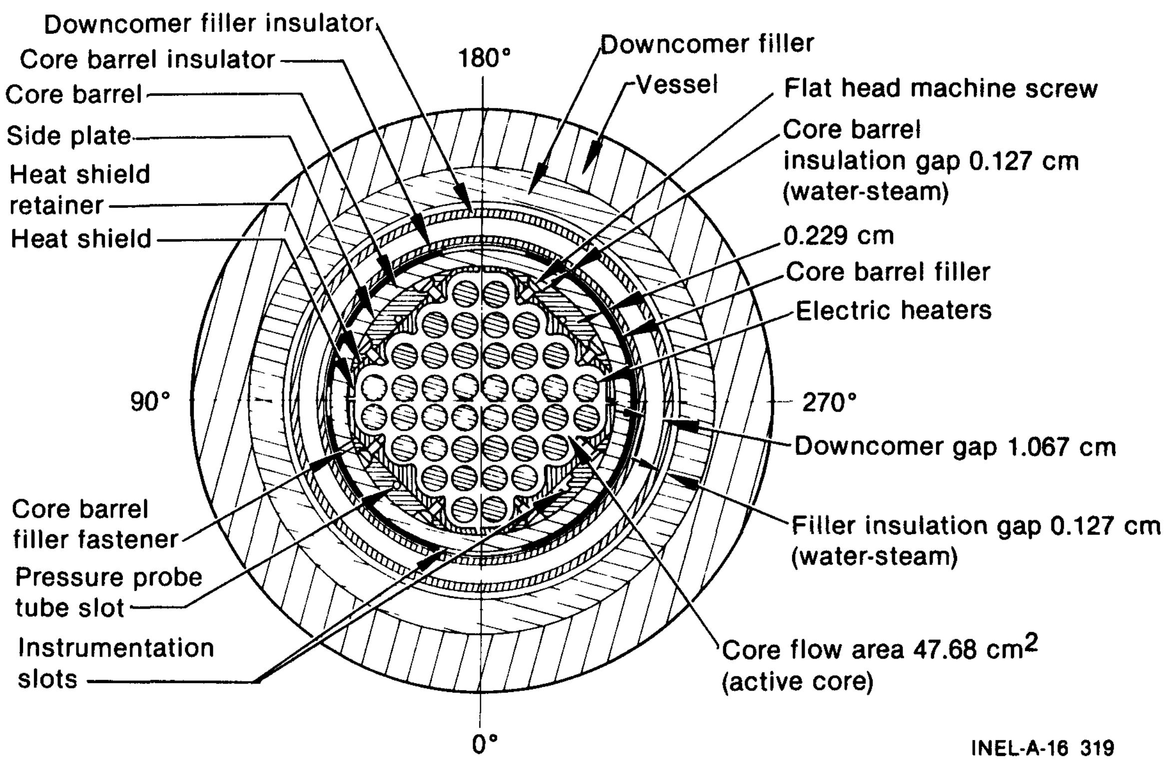

Figure 3. Semiscale Mod-1 vessel cross section and core layout.

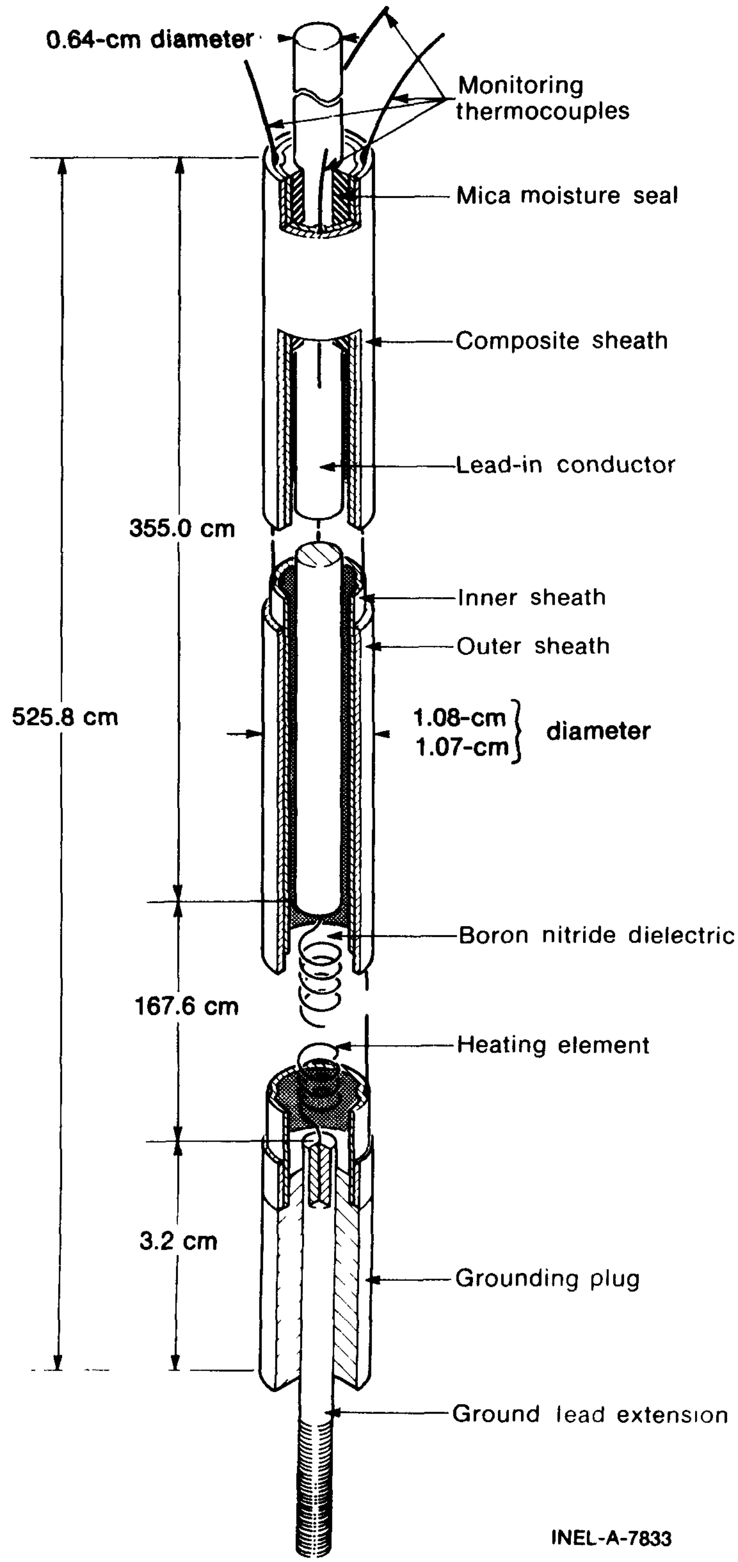

Figure 4. Semiscale Mod-1 electric heater rod.

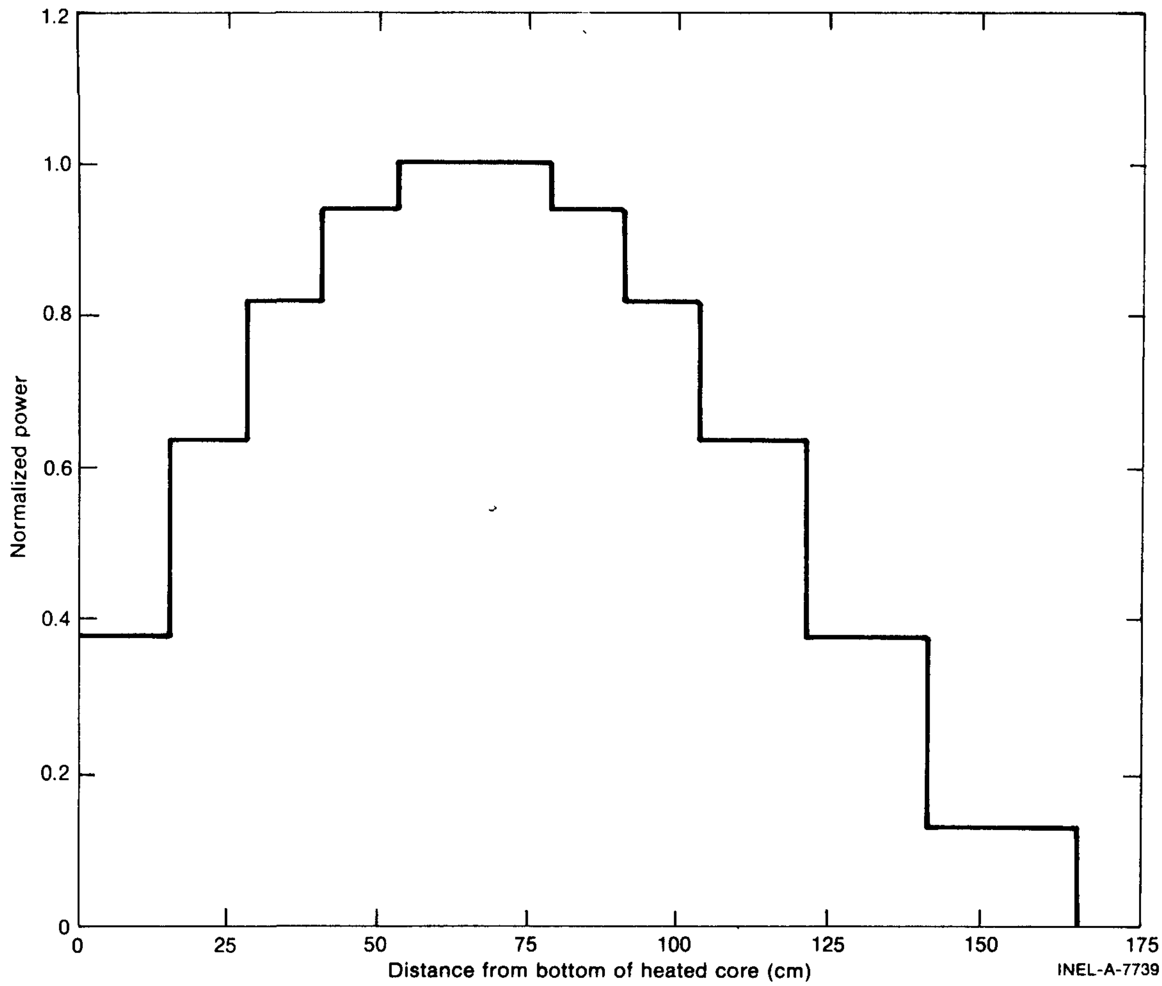

Figure 5. Semiscale Mod-1 heater rod axial power distribution showing ratio of local power to peak power.

thermocouple junction to the grounded end of the inner sheath were filled with 0.064-cm welding wire, which was laser beam tack welded in place. The outer sheath was positioned over the inner sheath after installation of the thermocouples, and the composite assembly was redrawn. The thermocouples provided rod cladding temperature measurements at four different axial locations along the 1.68-cm heated length of the heater rods.

The 40 rods were positioned and held in the core with 10 grid spacers that maintained the heaters on a typical PWR pitch (1.43 cm), as was shown in Figure 1. Figure 6 illustrates the heater rod matrix

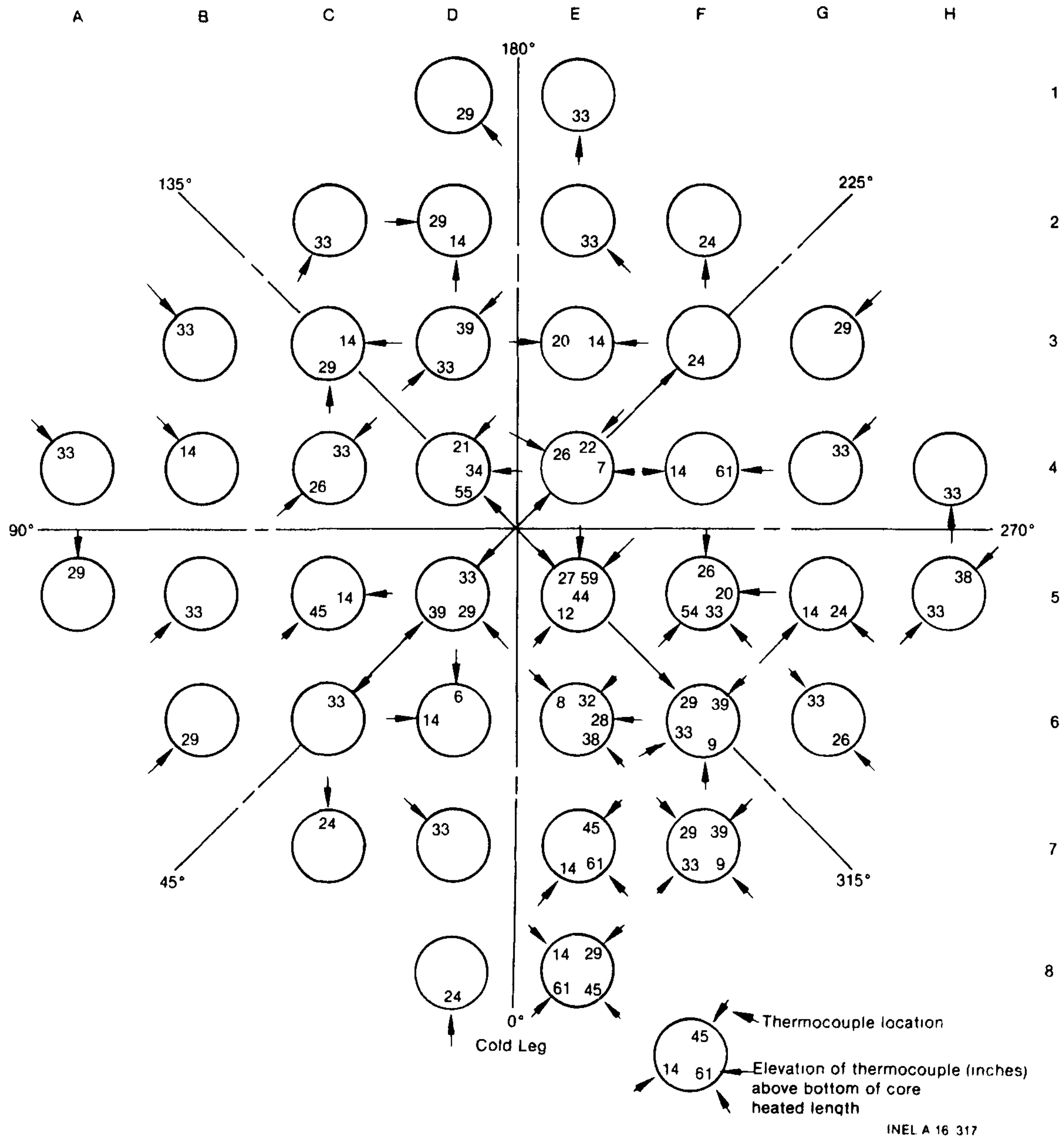

Figure 6. Semiscale Mod-1 heated core - plan view showing instrumentation.

and cladding thermocouple locations. The heater rods were located within the matrix by reference to the row of letters across the top and the column of numbers down the side of the matrix (Figure 6). Similarly, the thermocouples were located by the rod they are on and by their elevation above the bottom of the heated length of the core. The thermocouple on Rod D5 at the 73.7-cm elevation was thus referred to as TH-D5-29, where TH means a core heater cladding temperature, D5 refers to the rod upon which the thermocouple is located, and 29 gives the thermocouple elevation in inches above the core bottom. (The arrows in Figure 5 indicate thermocouple azimuthal locations.)

A heat shield assembly composed of 0.117-cm-thick stainless steel surrounded the rod matrix and reduced the core flow area to 47.68 cm^2. The four centrally located rods (the high power rods) individually produced 66.23 kW (62.5 kW/m maximum linear heat rate) at 173 Vdc (nominal resistance of 0.453 ohms), and the remaining 36 rods (the low power rods) each produced 36.9 kW (34.8 kW/m maximum linear heat rate) at 173 Vdc (nominal resistance of 0.811 ohms). These different profiles allowed the simulation of the radial peaking that exists in nuclear cores. A sufficient factor of safety was built into the rods to allow for the implementation of a flat radial power profile on the core simulator if desired. When assembled in the core simulator, the 40 rods produced a total core power of 1.6 MW.

3.66-m Heater Rods

As stated earlier, the 3.66-m rods used in the Semicale Mod-3 system are of the same basic design as the 1.68-m rods. The major differences are the length of the heated section, the number of thermocouples (6) along the heated length, the number of rods, and the operating voltage. Twenty-four rods capable of producing 116 kW each (49.2 kW/m peak linear heat rate) at 380 Vdc were employed in the Mod-3 system. The nominal element resistance was 1.245 ohms.

TESTING OF THE CURRENT ROD DESIGN

Qualification testing and rod response and analysis during numerous transient tests that have been conducted using the heater rod design will be discussed in this section. Since the majority of the testing and analysis has been conducted on the Mod-1 heater rod design, the discussion will be limited to the 1.68-m rods.

Qualification Tests

The Mod-1 heater rods were tested at Columbia University to demonstrate their capability to operate in the expected test environment and to obtain supplemental data, such as thermocouple reliability, on heater performance. Heater rod prototypes were subjected to a series of warmup, blowdown, and reflood thermal cycles similar to conditions under which the rods would operate in the Semicale Facility. A secondary objective of the tests was to obtain information regarding the rod failure margin during repeated operation at excessively high rod temperatures (above design values).

The heater testing was performed in the Chemical Engineering Research Laboratory at Columbia University. The heaters were installed in a small bypass loop that was, in turn, attached to a larger pressurized water test loop, shown in Figure 7. The larger loop provided the source of high pressure hot water for flow through the heater test section. Isolation valves were provided to permit a blowdown of the test section without also blowing down the main loop. A source of simulated emergency core coolant injection water was also provided. Parameters measured and recorded during the tests, in addition to the heater sheath thermocouple measurements, included test loop inlet and outlet water temperatures, loop pressures, flow rates of the circulating and reflood water, and the time of test section blowdown initiation. Each test cycle consisted basically of: (a) warmup to full power; (b) system blowdown with full power on the heaters until a preselected cladding temperature was obtained, with a reduction to 6% power thereafter; (c) a water reflood initiated at a cladding temperature of 1230 K; and (d) a reduction to zero power at a cladding temperature of 1310 K.

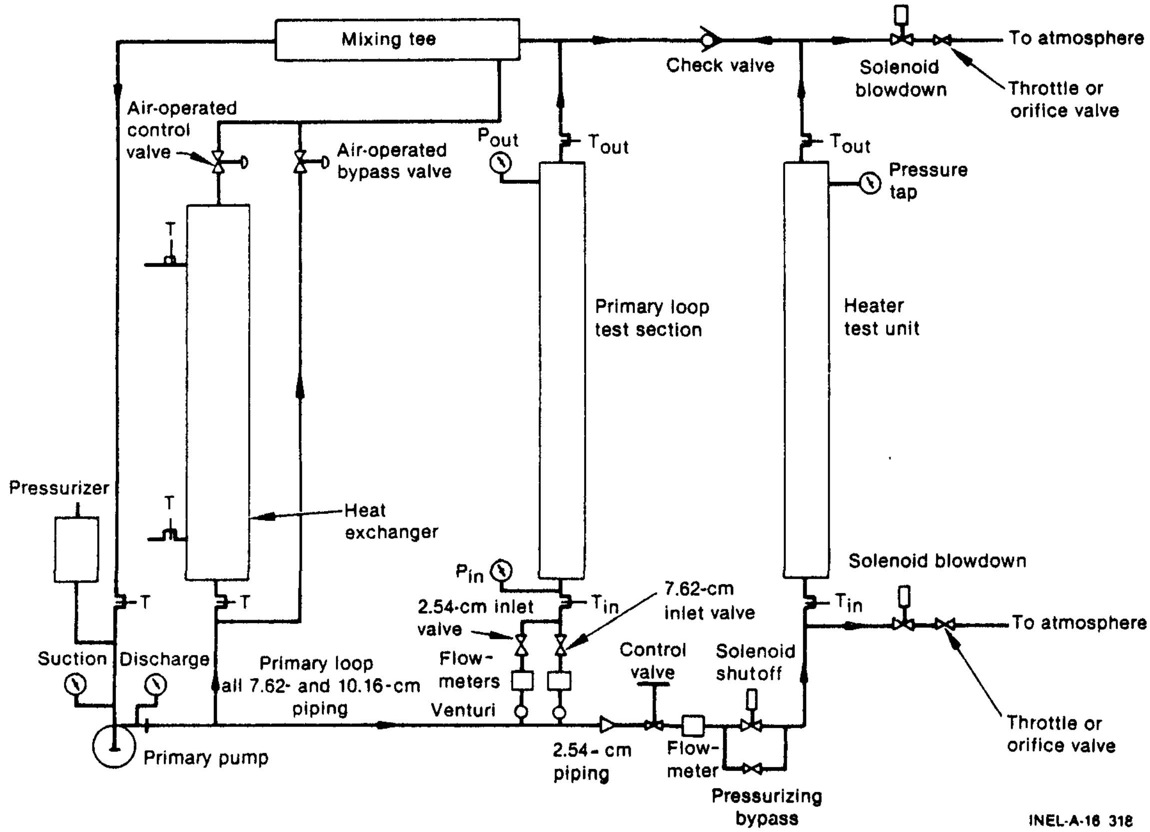

Figure 7. Test system diagram.

The minimum acceptable service life for the heater was specified as ten blowdown cycles. To successfully pass the qualification test, each heater was required to be operable within ±10% of the rated power at rated voltage after completion of the series of ten blowdown cycles. A bundle of three heaters that sucessfully passed this qualification test program with zero failures would provide a 95% confidence level that the mean time between failures of a heater would be equal to or greater than ten blowdown cycles under the most severe blowdown conditions expected. Minor dimensional or electrical changes were not considered to be test failures.

Heater Qualification Test Results

A bundle consisting of three low power heaters was subjected to eleven test cycles. No heater failures occurred and the average and maximum rod electrical resistance changes were 1.5 and 3.6% of the initial value, respectively. Of a total of 12 cladding thermocouples, 3 of them failed during the 11 tests. Posttest examination of the rods indicated no apparent damage, although rod bowing was evident, as was expected.

A three-rod, high power heater bundle was subjected to the same test conditions as the low power bundle. One of the heaters failed (at an indicated cladding temperature of 950 K) during steady state, full-power operation prior to the ninth test. Posttest investigation revealed that an instrumentation error had inadvertently caused the bundle to be subjected to 120% of the specified test power, which probably contributed to the heater failure. Examination revealed that a 0.65-cm hole had been burned in the high power zone of the failed heater. The two undamaged rods were subjected to the required ten cycles, and no additional failures occurred. The average electrical resistance change was found to be 0.42% of the initial resistance value for the two unfailed rods. As with the low power bundle, three thermocouples failed during the high power bundle tests; one of the failed thermocouples was due to the heater failure. Posttest examination showed that all of the heaters were bowed in the high-power zone.

Heater Destructive Test Results

The destructive tests were basically the same as the qualification tests and were conducted on a high power rod to determine an appropriate maximum cladding temperature at which the heater power should be reduced to a low value in order to prevent rod failure. The full-power trip was initially set at 1033 K, and was then increased by 14-K increments for each additional test. The heater failed during the sixth test at an indicated temperature of 1116 K. Examination of the failed rod showed that significant arcing had occurred in the high power zone and had produced a large hole in the cladding.

Conclusions reached from the results of the qualification test were that even though one rod failed, the fact that it survived eight tests at 120% of maximum power was sufficient to warrant acceptance of both the low and high power heaters. On the basis of the test results, the 950-K cladding temperature was selected as the full power operation cladding temperature limit in lieu of the 1033-K value. This limit was increased to 1033 K after significant operating experience with the full core indicated that it was safe (and necessary) to do so.

TRANSIENT TESTS

As stated in an earlier section, more than 50 blowdown-type experiments and 12 separate effects reflood experiments were conducted in the Semiscale Mod-1 facility. The first series of experiments in which the heated core was used was denoted Test Series 2 (the Blowdown Heat Transfer Test Series)[7], and the heater rod behavior during this group of tests has been carefully analyzed.[8] It was during this series of experiments that control techniques required for the simulation of nuclear rod behavior with the electrical heaters were determined, rod cladding temperature behavior was analyzed from a rod construction viewpoint (in addition to thermal-hydraulic effects), and estimates of uncertainties in actual rod geometry and electrical properties were addressed. The following sections discuss some of these areas.

Transient Power Control

One of the requirements for using electrical resistance heaters in the simulation of PWR fuel transients is that the surface temperature of the electrical heater rods behave in a fashion similar to that expected of nuclear rods. An examination and comparison of the thermal properties of the materials used in the construction of the electrical and nuclear rods suggests that the power supplied to an electrical rod in the simulation of a transient cannot simply be equivalent to nuclear fuel decay heat. This is evident from an examination of the thermal properties in Table 1, which presents a comparison of the thermal conductivity, density, specific heat, and thermal diffusivity at two different temperatures for the principal components of the nuclear and electrical rods. The values in Table 1 show that the thermal conductivity, specific heat, and density of the principal rod components by volume (boron nitride and uranium dioxide) are significantly different; the thermal diffusivity of UO_2 is nearly a factor of three less than that of boron nitride. A comparison of the calculated steady state radial temperature profiles (Figure 8) for an electrical rod and a nuclear rod operating at 36.1 kW/m linear heat rate illustrates the effect of the property differences on the temperature and stored energy distributions. An additional property limitation of the electrical rod is that due to filament limitations (melting); the peak centerline temperature limit is lower than that for a nuclear rod.

TABLE 1. COMPARISON OF SEMISCALE HEATER ROD AND NUCLEAR FUEL ROD MATERIAL THERMAL PROPERTIES AT TWO DIFFERENT TEMPERATURES

	Thermal Conductivity, k (W/m·K)		Density, ρ (g/cm^3)		Specific Heat, cp (J/kg·K)		Thermal Diffusivity, α (cm^2/s)	
	600 K	900 K	600 K	900 K	600 K	900 K	600 K	900 K
Boron nitride	13.25	10.2	2.01	2.01	1435	1835	4.59×10^{-2}	2.77×10^{-2}
Uranium dioxide	5.45	3.72	10.96[a]	10.96[a]	296.9	313.7	1.67×10^{-2}	1.08×10^{-2}
Stainless steel (316L)	17.74	21.19	8.03	8.03	543.7	595.9	4.06×10^{-2}	4.43×10^{-2}
Zircaloy-4	16.95	20.41	6.56	6.56	317.8	347.1	8.13×10^{-2}	8.90×10^{-2}

a. Theoretical.

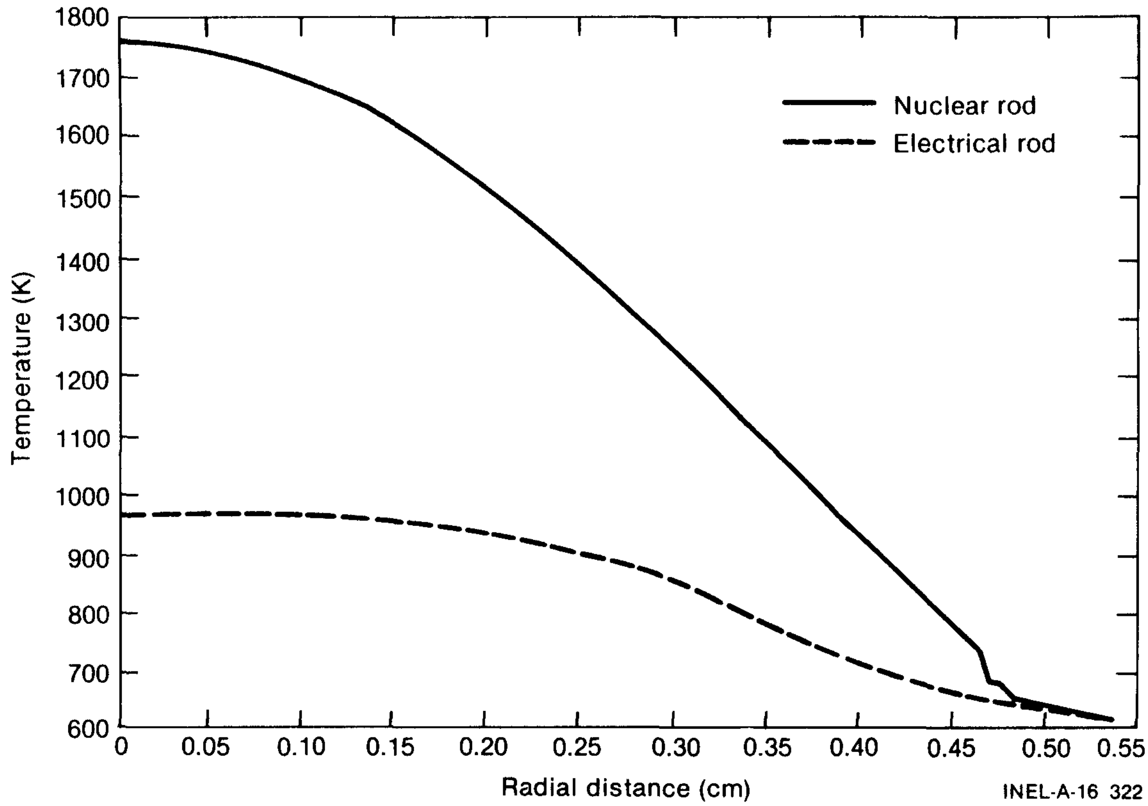

Figure 8. Comparison of nuclear and electrical rod radial temperature profiles.

The criterion for selecting an electrical rod power control is that it must cause the surface temperature of an electrical rod to approach as closely as possible the surface temperature calculated for a nuclear rod. This criterion was met by matching the transient surface heat flux calculated for an electrical rod with that calculated for a nuclear rod, assuming both rods were subjected to the same transient boundary conditons. These calculations were performed using one-dimensional analytical heat conduction models of the electrical and nuclear rods. In all cases, the power decay curve applied to the nuclear rod was the proposed standard power decay discussed in Reference 9. Since the Semiscale electrical heater rods had a fixed axial peaking factor of 1.58, use of the technique described to specify the core power control allows the electrical and nuclear rod surface heat fluxes to be matched at only one axial location. The rod axial location of peak power generation (the hot spot) was the point at which the nuclear and electrical fluxes were matched, because the cladding temperature response at this location was of prime concern during the Blowdown Heat Transfer Test Series.

The initial core power profile used in the Semiscale Blowdown Heat Transfer tests was derived using the method of heat flux matching described above, assuming that the heat transfer mechanism at both rod surfaces was nucleate boiling for the entire blowdown transient. As a result of this assumption, the power profile caused the electrical rod response to closely simulate a nuclear rod only up until the time at which departure from nucleate boiling (DNB) occurs. To provide better representation of a nuclear rod, improved post-DNB core power controls were used for later experiments. In the improved case, measured data (core fluid temperature, rod heat transfer coefficients, etc.) from experiments were used as transient input boundary conditions for the analytical models. A comparison of the nuclear decay heat, the initial electrical power, and the improved electrical power is shown in Figure 9. An obvious drawback of this method of power control is that it is applicable only for one particular transient, and an iterative procedure must be used to define the appropriate power. An improved technique for controlling the electrical power during blowdown experiments is discussed in Reference 10.

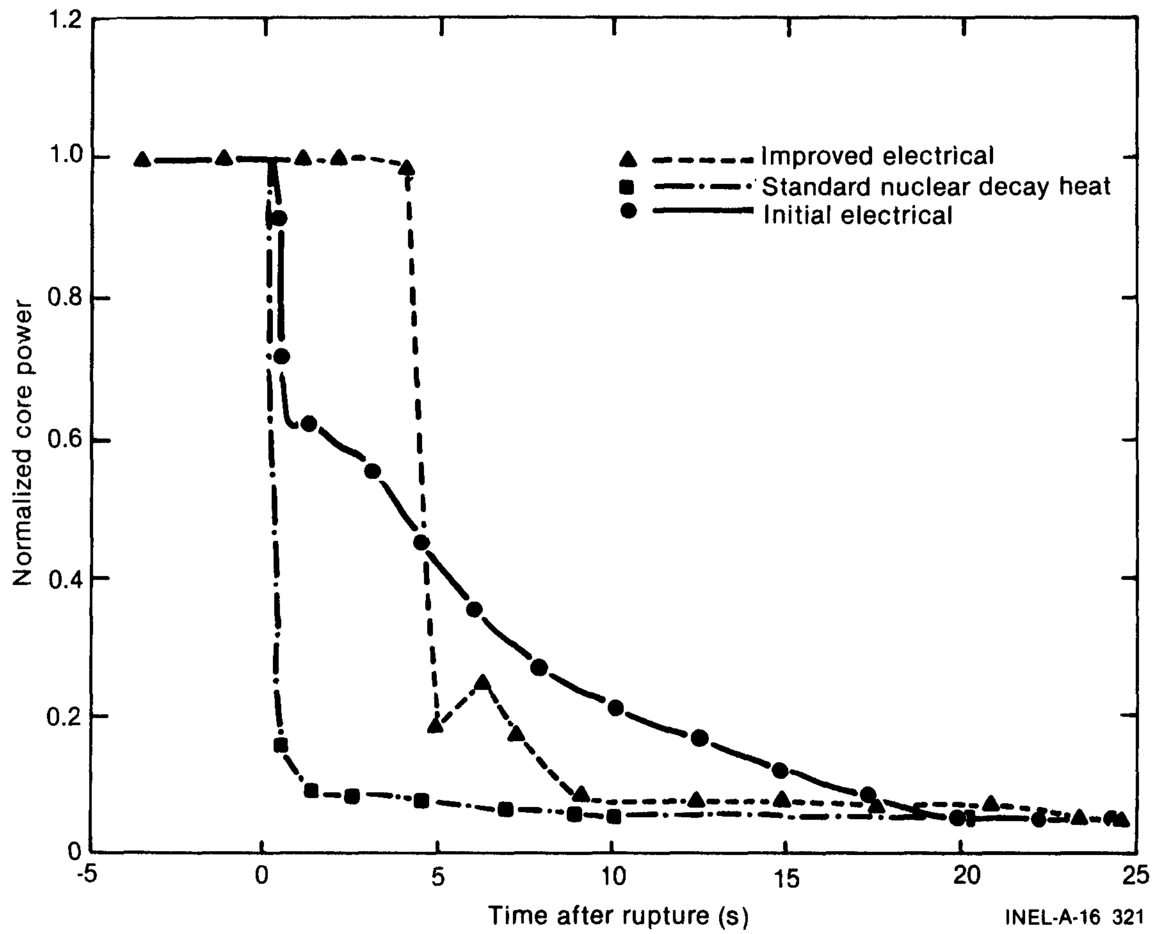

Figure 9. Normalized transient core power.

Heater Rod Behavior During Blowdown Tests

Both hot and cold leg break loss-of-coolant transients were conducted during the course of the Semiscale Mod-1 program. The heater rod behavior during the hot leg break experiments was generally as expected. A sustained positive core flow caused the cladding temperature to essentially follow system saturation temperature until complete core dryout (fluid quality approached unity) caused the cladding to begin heating up. The core behavior during cold leg break experiments was generally characterized by departure from nucleate boiling shortly after the initiation of the transient (0.5 to 3.0 s), and a resultant rod cladding temperature increase to values approaching 1050 K. A comparison of typical rod cladding temperatures for the hot and cold leg break experiments is shown in Figure 10. In many cases during the cold leg breaks, rewetting (a phenomenon whereby sufficient liquid comes into contact with the rod surface after DNB to cause a significant increase in the heat transfer rate until rod surface dryout again results in a degradation in heat transfer) of various heater rods occurred. The occurrence of rewetting causes energy that would

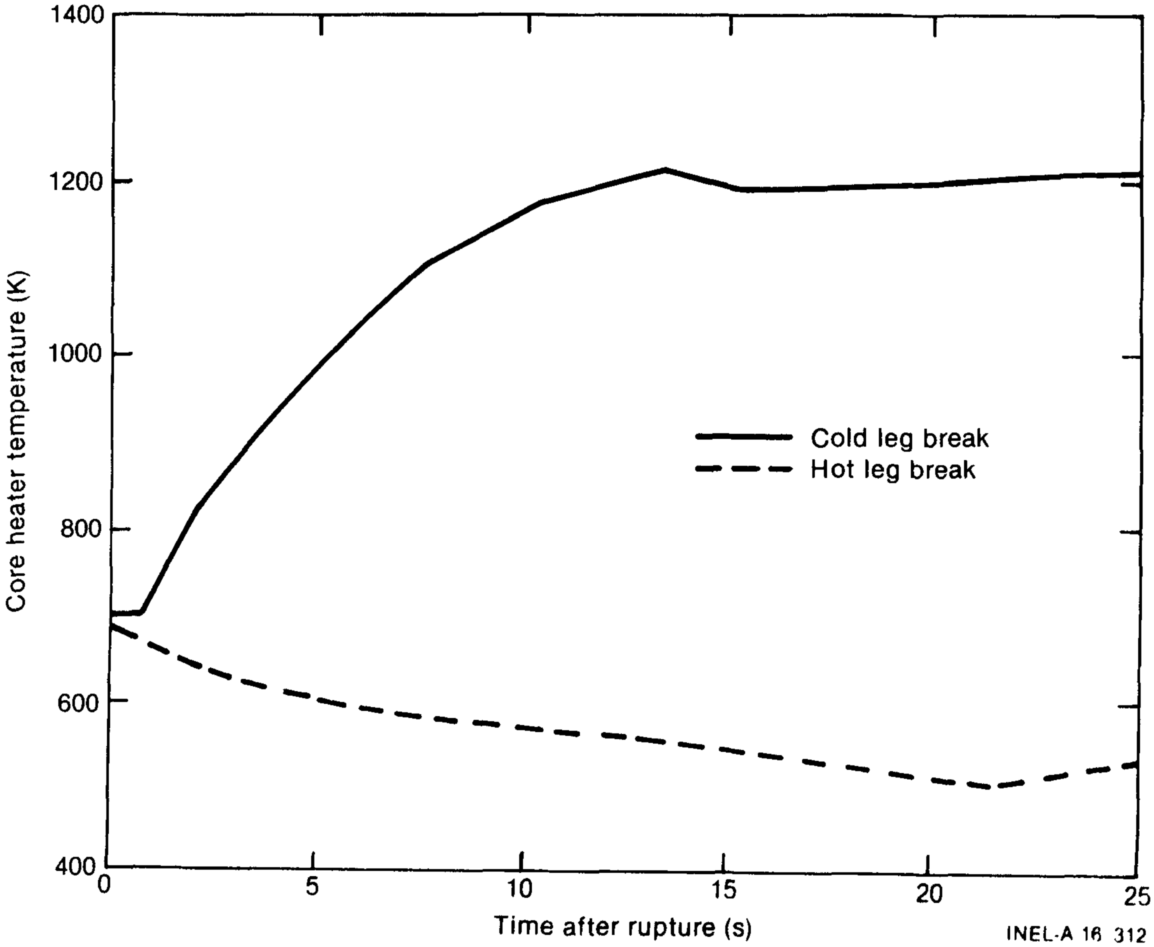

Figure 10. Comparison of rod high power zone temperature response for hot and cold leg break loss-of-coolant experiments.

otherwise be stored in the rod (consequently contributing to rod temperature rise) to be removed. Rewetting is then an important consideration because a rewetted condition generally results in lower rod cladding peak temperatures. This difference in cladding peak temperature is illustrated in the Figure 11. The results shown in the figure were somewhat unexpected in that although the thermocouples shown are on adjacent rods, the thermocouples face the same fluid subchannel and, therefore, should experience similar fluid conditions. One postulated explanation for the behavior was that signficant differences existed in the rod local linear heat rate. However, detailed analysis of rod local linear heat rates (discussed below) have failed to explain the behavior shown in Figure 11.

Azimuthal, radial (core wide), and axial variations in the rod rewet behavior were noted during the numerous experiments conducted. Slight azimuthal variations were verified by studying cladding temperature behavior on a rod that had more than one thermocouple at nearly the same axial location. The behavior differences were noted to be rather minor and can be attributed to slight local fluid condition variances and possible thermocouple radial location variances (although data presented in Reference 11 suggest that thermocouple location influences should be minor).

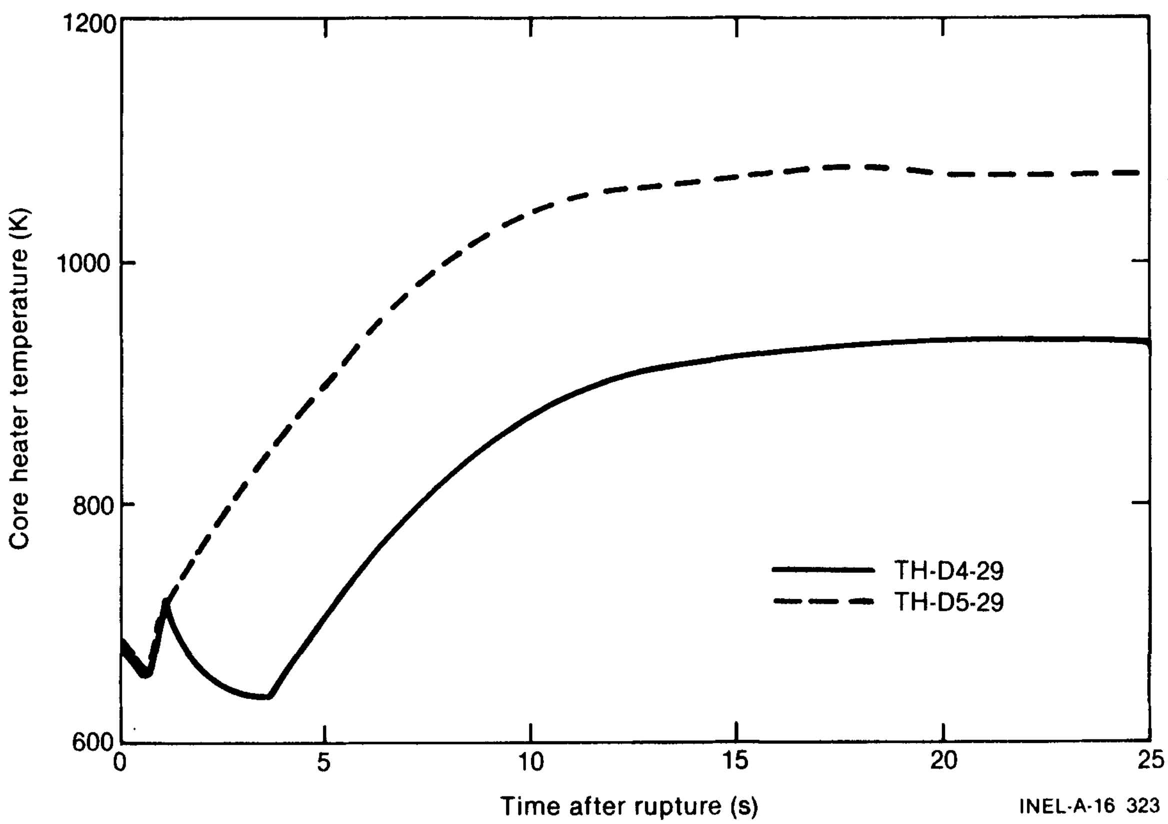

Figure 11. Comparison of the response of two 73.7-cm elevation thermocouples that both face the core central fluid channel.

Radial distributions of the core DNB and rewet behavior were investigated by considering selected groups of rods and tabulating the rewets in each group. Grouping of the rods on a quadrant basis (i.e., upper left, lower left, upper right, and lower right as shown in Figure 6) indicated that more rewets (on a percentage basis) occurred in the upper left and lower right quadrants. Analysis of the average rod electrical resistance suggested that this behavior could have been partially attributed to lower power generation (higher resistance) in these quadrants, although the quadrant-to-quadrant resistance variation was relatively small.

Grouping the rods in other ways failed to reveal any pattern in the radial rewet behavior. The rewet distributions did not seem to correlate with any physical rod parameters. In fact, it appeared that any radial pattern may have been overshadowed by the effects of axial location of the thermocouples within a given power zone and the axial rewet distribution in general. Analysis of DNB and rewet characteristics of all thermocouples from several similar experiments showed a pronounced trend in rewet behavior as a function of axial position. The heated length of the core could be divided into distinct axial regions on the basis of DNB and rewet phenomena occurring within these regions. These divisions did not necessarily coincide with the axial power step divisions. The heated length of the core could be categorically divided into the following regimes:

1. Early DNB without rewet

2. Early DNB without rewet and early DNB with rewet

3. Delayed DNB and early DNB with rewet.

The axial distribution of rewet behavior is shown in Figure 12. The different shaded regions in this figure correspond to the regimes discussed. The figure shows that a definite axial pattern existed in the Semiscale core rewet phenomena. This axial dependence existed for all of the flat radial power profile tests conducted, suggesting a strong relationship between local power density, fluid conditions, and whether or not a rod is able to rewet. Two definite regions existed (approximately 0 to 27.9 cm and 43.6 to 66.0 cm above the bottom of the heated length) in which rewets did not occur. Apparently, the fluid quality and power density in these regions were such that rewetting was prohibited. However, thermocouples at elevations between 33 and 38.1 cm and between 68.6 and 78.7 cm contained a mixture of rewets and some nonrewets. The relationship between fluid quality and power density here must have been such that rewetting is possible but not certain. Upper core thermocouples between 81.3 and 99.1 cm indicated a variety of responses, including delayed DNB and early DNB with rewets. Thermocouples at elevations above 99.1 cm indicated either delayed DNB or no DNB. The variation in thermocouple response noted for the upper core elevations was probably due to radial variations in fluid conditions.

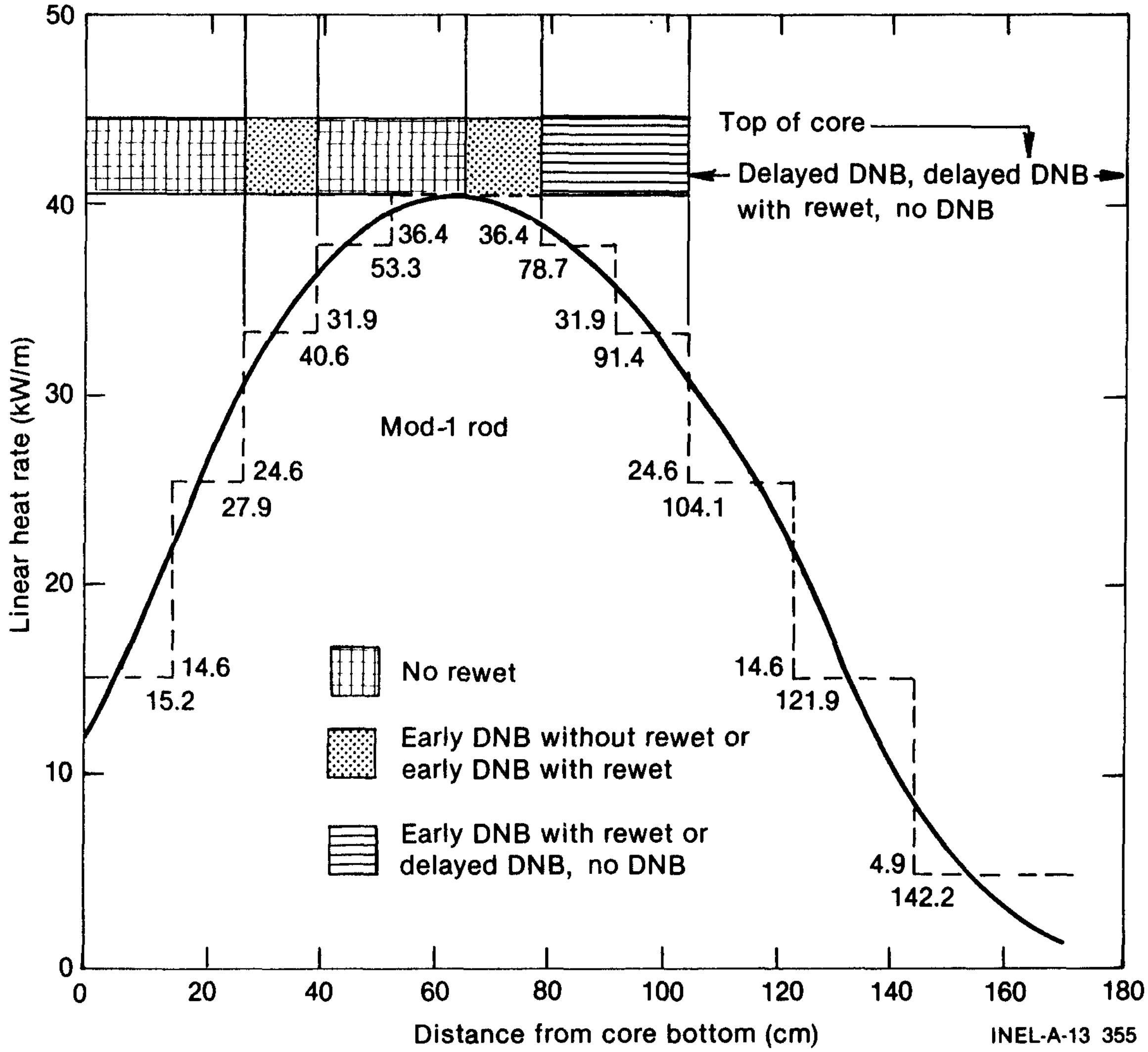

Figure 12. Axial distribution of rewet behavior, Test S-02-7.

In addition to the suspected strong relationship between rod power density and fluid quality with reference to the rod rewet phenomena, flow maldistributions in the core due to the grid spacer locations could possibly infuence the occurrence of rewetting. Three grid spacers were located along the heated length of the rods at elevations of 44.2, 86.4, and 128.5 cm above the core bottom. The grids at 44.2 and 86.4 cm were located directly above the two zones in the core in which a mixture of both rewets and nonrewets occurred. The presence of the grids could possibly bias the flow in a reverse core flow situation in such a manner as to affect the rewetting characteristics for some distance downstream of the actual location of the grid spacer.

A reasonable additional postulation is that if the proper combination of fluid and heater rod surface conditions exist (such as surface flux and surface roughness), rewetting could propagate axially from upper core elevations to lower core elevations. The point of the rewet penetration into the high power zone on the Semiscale heater rods appeared to be a function of the initial peak power density. If the peak power density is plotted against the high power zone elevation below which rod rewetting does not occur, the result is a straight line as shown in Figure 13. This result tends to indicate that the

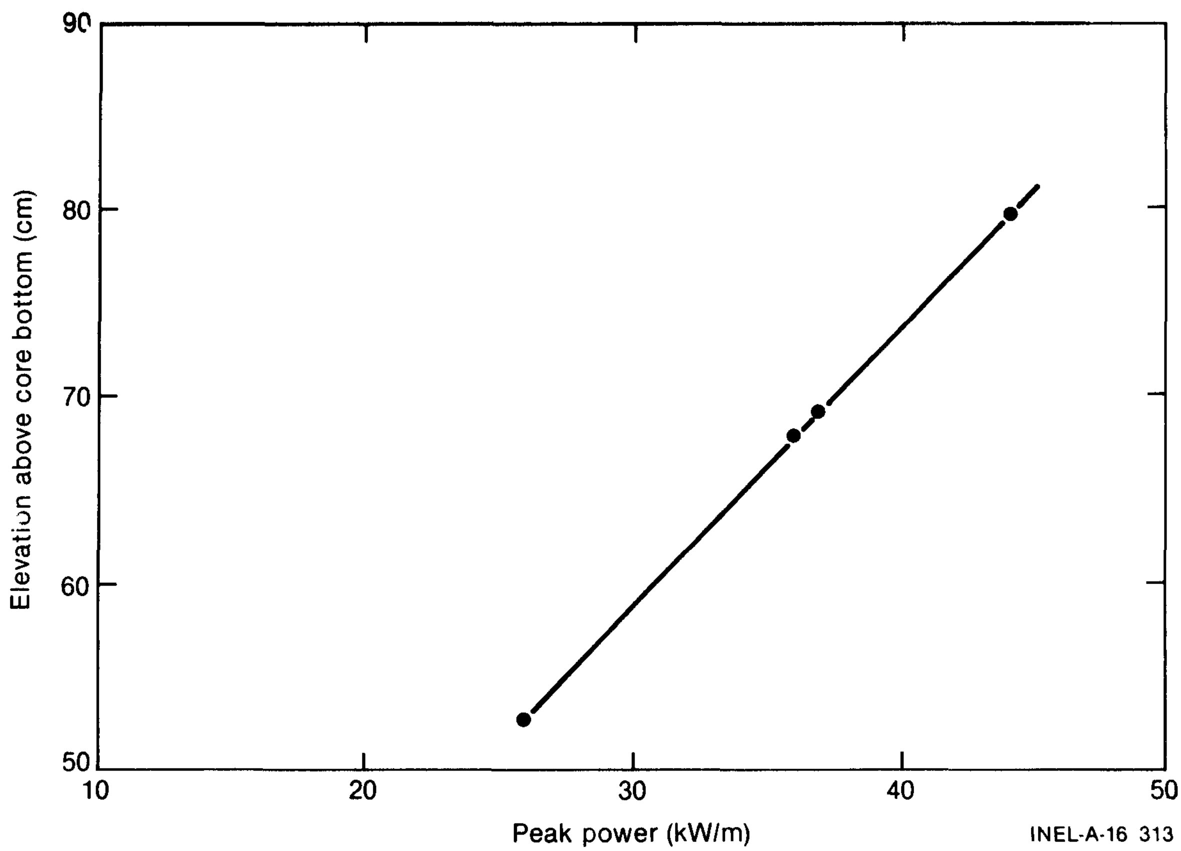

Figure 13. Axial penetration of rewets into rod high power zone versus rod peak power density.

relationship between power density and fluid quality plays an important role in determining whether or not a rod will rewet. The axial quality gradient was not expected to be significantly different for any of the 100% power tests; however, as shown in Figure 13, differences in the peak power density had a noticeable effect on the rewet behavior during the rod peak power step. Comparisons of cladding thermocouple DNB and rewet behavior from three similar experiments indicated that the core thermal response during the Blowdown Heat Transfer Test Series was repeatable. The cladding temperature response was shown to be repeatable, with a few exceptions at all axial elevations in the heated core. Although some exceptions were noted along the upper 10 cm of the rod high power zones, the rewet phenomena that occurred at the rod hot spots during the three experiments were shown to be highly repeatable.

The numerous blowdown tests conducted in the Mod-1 system verified the repeatability of the core thermal response and the heater rod design. Throughout the course of the repeated rod heatup and cooldown cycles (more than 15 in Test Series 2 alone),[a] only three heater rods failed (due to resistance element electrical shorting to the cladding). The cladding thermocouples and installation procedures were also shown to be reliable since more than 50% of the thermocouples were still functional when the original core was replaced.

Analysis of Rod Local Power Density

The thermocouple response shown in Figure 11 and the rewet behavior of the core in general prompted the conduct and analysis of special tests in search of reasons to explain the thermocouple behavior differences. In particular, the analysis was directed toward an attempt to identify heater rod power density variations.

The data used in the analysis of the Semiscale heater rod power density variations included

1. Steady state cladding temperature values
2. Power pulse test data
3. Heater rod infrared scan profiles
4. Heater rod X-ray photographs
5. Dry core heatup data.

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a. Some of the heater rods used during the Blowdown Heat Transfer Test Series were used in subsequent reflood and integral blowdown-reflood tests, and were therefore subjected to many more cycles.

Comparison of the steady state cladding temperatures from all of the thermocouples at a given core elevation indicated some variation in the initial values of the temperature from rod to rod. The temperature variations, although relatively small, seemed to imply that differences did exist in the characteristics of individual rods. However, many possible reasons exist for the variation in steady state temperature. A few possibilities are:

1. Radial location of the thermocouple beneath the cladding surface

2. Local power density variations

3. Thermocouple contact resistance

4. Azimuthal location of the thermocouple in relation to the heater coils

5. Thermocouple measurement errors

6. Flow maldistribution within the core

7. Errors in the actual thermocouple elevation

8. Variations in the individual rod material thermal properties.

Power Pulse Test Data Analysis

Special tests (termed "power pulse" tests) were conducted on the electrical core prior to each blowdown in an attempt to detect changes in the rod material thermal properties. The tests were conducted by applying a step change to the core voltage, maintaining the voltage for about 10 s, and then returning the voltage to its initial value. These tests were conducted while the core was operating at low power (about 150 kW), and the peak power applied to the core was generally about 550 kW. Figure 14 shows the response of thermocouples at the same axial elevation (74 cm) on two different rods (D4 and D5) to the pulse test conducted prior to a blowdown test. Also shown in the figure is the predicted response, which was calculated with a one-dimensional heat conduction model of the Semiscale electrical rod. The prediction agrees quite well with the behavior of the thermocouple on Rod D5. The power input to the model had to be reduced by about 13% in order to duplicate the measured behavior of the thermocouple on Rod D4. However, the power generation of Rod D4 was not necessarily 13% lower than that of Rod D5. In applying the conduction model, the assumption was made that the two rods were identical in terms of material properties, thermocouple location, and thermocouple contact resistance. This assumption probably did not represent the true conditions exactly. The difference in response of Rods D4 and D5 during the pulse test was, however, in agreement with the behavior of the rods as indicated by the thermocouples during blowdown (the thermocouple on Rod D5 did not experience rewet).

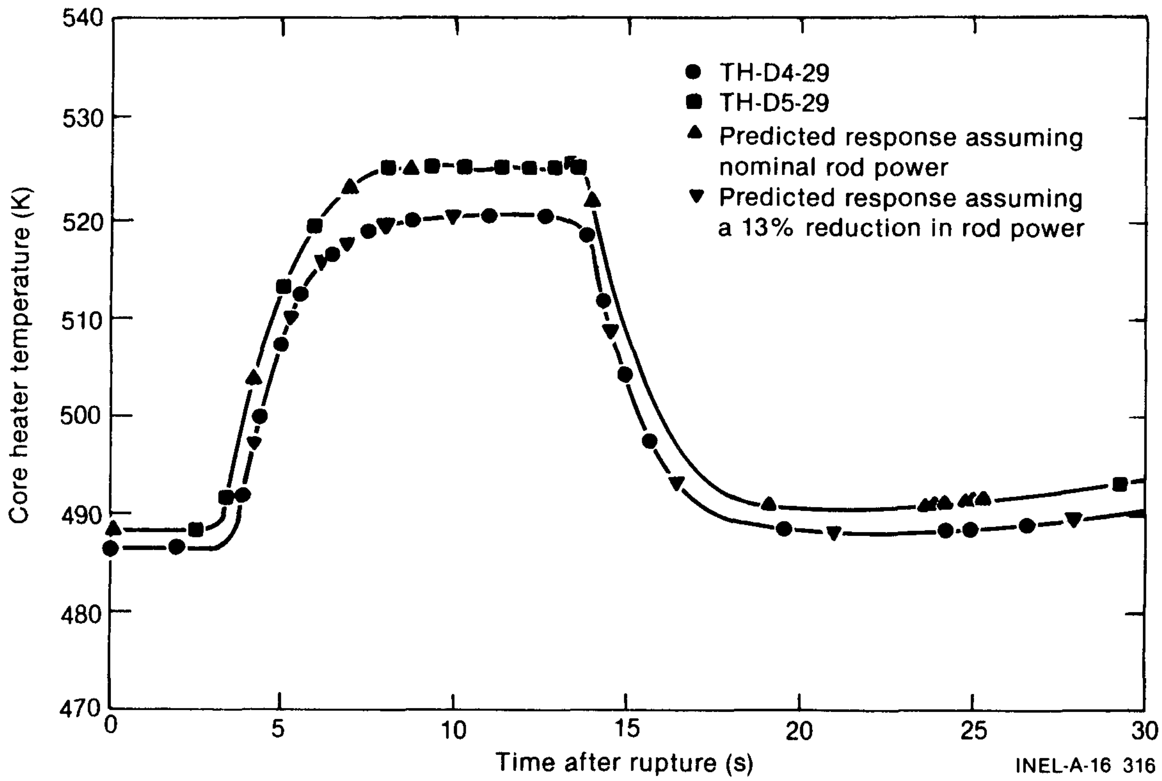

Figure 14. Measured and predicted response of Thermocouples TH-D4-29 and TH-D5-29 during pulse test.

The response of the hot spot to the power pulse tests was analyzed by computing the maximum temperature difference (ΔT) attained during the course of the pulse test. The following equation was used to calculate the temperature difference.

$$\Delta T = \left[T_{TC} - T_f(Z)\right]_1 - \left[T_{TC} - T_f(Z)\right]_2 \qquad (1)$$

where

T_{TC} = measured thermocouple temperature

$T_f(Z)$ = fluid temperature at the thermocouple elevation.

The subscripts 1 and 2 refer, respectively, to the time prior to application of the power pulse and to the time when the temperature had stabilized after the power pulse was applied. The temperature differences attained at the rod hot spots are shown plotted against individual heater rod electrical resistance in Figure 15. Those hot spots that experienced rewet during the blowdown are also shown in Figure 15. The data indicate substantial variation in the values of the pulse ΔT of the individual rods. Seven of the twenty-four values plotted had a deviation from the mean ΔT value (32 K) that was larger

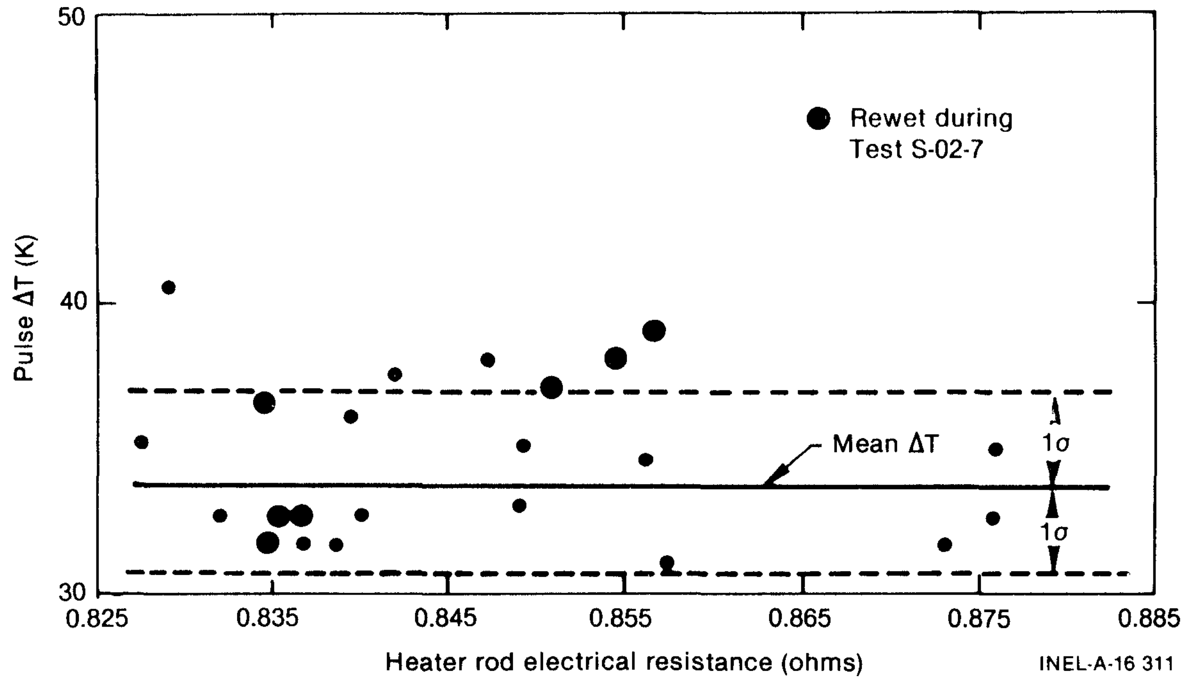

Figure 15. Heater rod hot spot temperature difference during pulse test versus rod electrical resistance.

than one standard deviation[a]. Also, four of the thermocouples that experienced rewet indicated a pulse ΔT above the average. If the pulse ΔT response was a good indication of rod power variation, then more rewets would probably be expected to occur on rods whose thermocouples indicated a lower-than-average pulse ΔT. Also, the larger the rod resistance (lower power generation), the lower the pulse ΔT would be expected to be. The data in Figure 15 do not reflect this expected correlation between rod resistance and pulse ΔT. The lack of agreement in the rewet, power pulse ΔT, and total rod resistance data led to an investigation of the local power density variation (variation within a given power step) on the Semiscale heater rod high power zones.

Heater Rod X-Ray and Infrared Scan Analysis

Both X-rays and infrared scans of the Semiscale heater rods were used in investigating the existence of local power density variations on the Semiscale rods. The infrared scan tests, conducted as part of the heater rod acceptance tests, were conducted by taking a series of infrared photographs of the heater rod while power pulses were applied to the rod in an air environment. Figure 16 shows an infrared scan of

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a. Hypothesis testing can be used to relate the sample mean to the nominal calculated mean from Figure 14. The null hypothesis that the calculated mean is the true sample mean must be rejected, however, indicating that the conduction model may require basic revision.

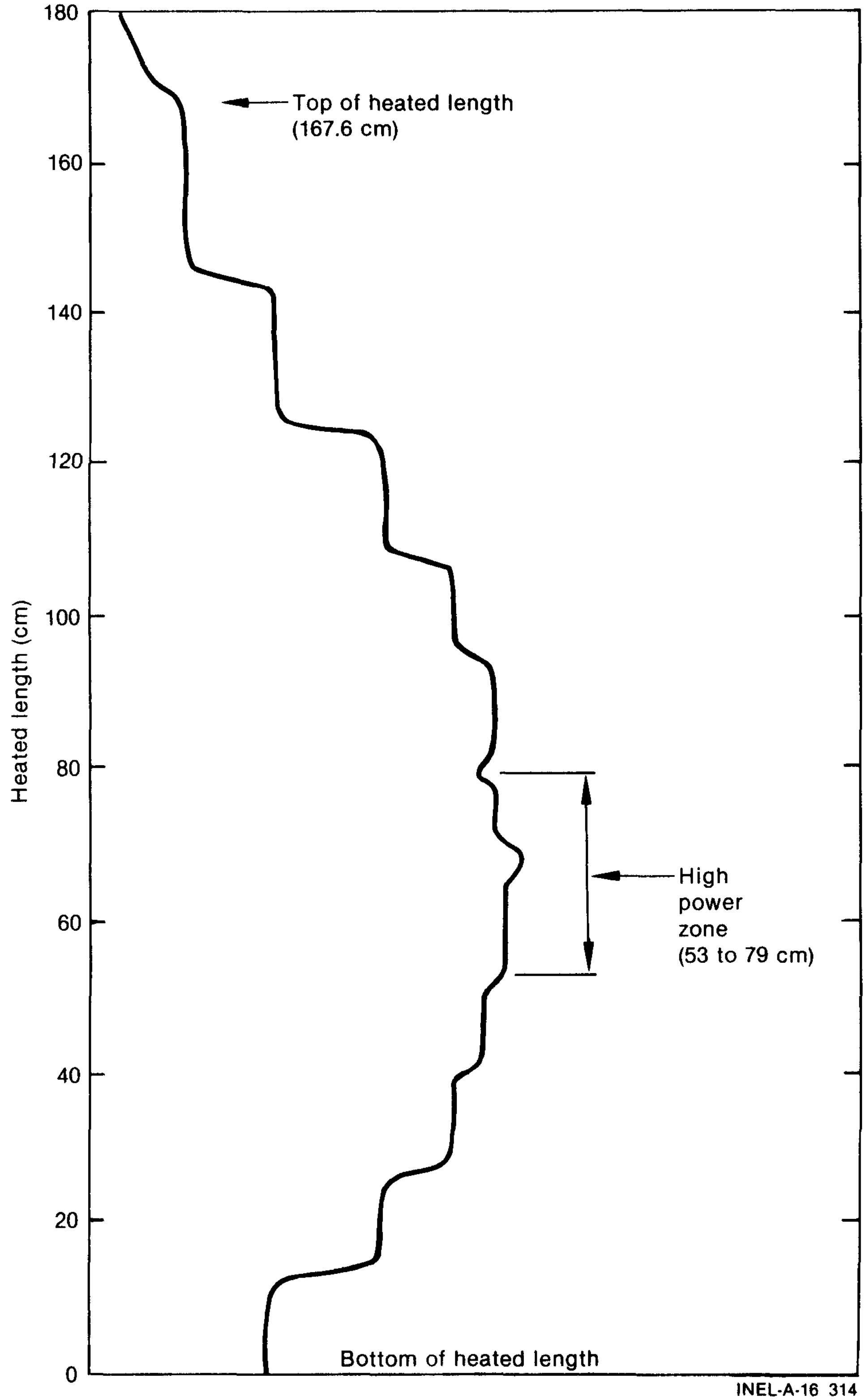

Figure 16. Infrared scan of Rod E5.

one of the heater rods. Locations where abnormalities were detected on the infrared scans, such as that indicated in Figure 16, were then investigated on the X-rays of the rods. In many instances, variations on the infrared scans could be correlated with differences in the local pitch on a given rod power step. For example, examination of the X-ray for the rod infrared scan shown in Figure 16 revealed that the pitch of the resistance wire in the rod varied about 6% in the vicinity indicated by the hump on the scan. Table 2 indicates the variation in effective coil wire length based on the measured pitch variations. Similar results were noted on other rods that were analyzed in this manner. Table 3 presents a comparison of the pitch and wire lengths of the high power zone resistance wire for several of the high power rods. The variations noted in the resistance wire pitch are not intolerable as far as the Semiscale tests were concerned. However, an important concern in the application of the analytical technique used to calculate rod heat transfer coefficients, surface fluxes, and surface temperatures from the measured data is the axial location of the thermocouples in relation to the power density variations. If the power input to the analytical model does not accurately reflect the rod power density, then incorrect results are obtained for the calculated rod surface flux and surface heat transfer coefficients. Attempts to improve the power input values for the analytical technique and perhaps partially account for thermocouple location relative to power density variations required a special Semiscale dry core heatup test.

Dry Core Heatup

The dry core heatup was conducted on the Semiscale system by stepping the core power from a low value to a higher specified value, maintaining the power for a short time, and then shutting the power off. This test was conducted with air as the medium surrounding the heater rods; the test was then essentially an adiabatic heatup of the core. The core was also reflooded at a very low flood rate subsequent to the power shutdown. The reflood portion of this test allowed quench times of the thermocouples to be compared for verification of their elevation in the core. New power factor multipliers were calculated by evaluating the slope ($\Delta T/\Delta t$) for each hot spot temperature measurement during the heatup portion of the test and then normalizing the individual slopes to the average slope. Consequently, a new power multiplier of less than 1.0 would indicate that, according to the thermocouple response during the dry heatup, the power density on that particular rod was somewhat less than the nominal desired power density. Similarly, a power multiplier larger than 1.0 would indicate a power density larger than nominal. The power multipliers calculated in this manner were verified by using them in conjunction with the analytical inverse heat conduction calculations to determine whether essentially zero rod surface heat fluxes were calculated as they should be, because the heatup was essentially adiabatic. Table 4 lists the new power multipliers calculated. Also indicated in Table 4 is whether or not the thermocouple experienced rewet during a representative blowdown experiment. Comparison of the data in the table does not indicate any correlation between the new power multipliers and the rewet characteristics. For example, some of the rewets occurred in zones that had power

TABLE 2. RESISTANCE WIRE LENGTH VARIATIONS IN ROD E5[a] HIGH POWER ZONE

Pitch (cm of rod/coil turn)	Length (cm of wire/cm of rod)
0.406	3.2782
0.416	3.2075
0.396	3.3544
0.422	3.1692

a. Serial Number 88112.

TABLE 3. COMPARISON OF AVERAGE PITCH AND RESISTANCE WIRE LENGTHS FOR THE HIGH POWER RODS

Rod (Serial Number)	Pitch (cm of rod/coil turn)	Length (cm of wire/cm of rod)
E4 (88102)	0.389	3.4125
D5 (8890)	0.410	3.2524
E5 (88112)	0.407	3.2708
D4 (88107)	0.412	3.2361
D5 (88118)	0.400	3.3274
E5 (88114)	0.408	3.2696

TABLE 4. POWER FACTORS CALCULATED FROM THE DRY CORE HEATUP TEST

Thermocouple	Power Factor	Rewet
TH-E5-21	0.90	No
TH-F3-22	0.9908	No
TH-F2-22	0.9825	No
TH-E4-23	0.9481	No
TH-G5-24	1.0263	No
TH-E5-25	0.9687	No
TH-D6-25	1.0126	No
TH-F3-25	1.0220	No
TH-F5-26	1.0331	No
TH-E4-27	0.9766	No
TH-C3-28	1.0296	Yes
TH-E6-28	1.0057	No
TH-F6-28J	1.0370	No
TH-C2-28	0.9838	Yes
TH-C5-28	1.0401	Yes
TH-D3-29	1.0258	Yes
TH-F7-29	1.0161	No
TH-A4-29	0.9989	Yes
TH-D5-29	0.9774	No
TH-B6-29	0.9964	No
TH-A5-29	1.0016	No
TH-B5-29	1.0360	No
TH-D4-29	0.9476	Yes
TH-E6-31	0.9781	Yes

multipliers larger than 1.0, and many rods that had calculated power multipliers of less than 1.0 did not experience any rewetting. In addition, the data taken during the core flooding conducted subsequent to the heatup tests verified (with only three possible exceptions) the axial location of the thermocouples.

In summary, the special tests conducted and analyzed have qualitatively substantiated the existence of power density variations both within the high power zone on a given rod and among the high power zones on all the rods. New power multipliers for the rod high power zones were developed using data from the dry core heatup test. The new power multipliers, when used in conjunction with the analytical technique used to calculate rod heat transfer quantities, did improve the results, but neither the pulse test differential temperatures or the new power multipliers seemed to correlate with the occurrence of rewetting in the rod high power zones. The reflood test conducted on the system verified that all but three of the high power zone thermocouples were located (axial position) where they were thought to be.

CONCLUSIONS

The qualification tests and numerous blowdown experiments conducted in the Semiscale Mod-1 system have verified the acceptability of heater rod design. The rods were shown to be reliable and the cladding thermocouples showed good survivability during the rigorous transient heatup and cooldown cycles to which the heater rods were subjected. Furthermore, the DNB and rewet behavior exhibited by the cladding during blowdown transients was shown to be repeatable. Although no definite, physically explainable pattern in the radial rewet behavior was evident, the behavior was repeatable. A definite, repeatable axial pattern was observed and was shown to be related to core grid spacer location, and the penetration of the rewet phenomena into the heater rod high power zone was dependent on the linear heat rate. Special tests and analyses conducted on the heater rods substantiated the existence of rod-to-rod linear heat rate variations and variations of the linear heat rate within a given rod power step. New power factors were derived from dry core heatup tests to account for rod-to-rod power variations. However, the rod rewet behavior could not be correlated to the rod power factors. The rewet behavior was speculated to be due to a combination of factors, including local fluid condition variations and rod local power variations.

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NOTICE

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